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REPORT AND DECISION ON REVIEW OF CERTAIN SOLVENT FLOOD OPERATIONS IN THE PEMBINA CARDIUM POOL

MAY 1967

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OIL AND GAS CONSERVATION BOARD
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OIL AND GAS CONSERVATION BOARD

MAY 1967

IN THE PEMBINA CARDIUM POOL
CERTAIN SOLVENT FLOOD OPERATIONS
REPORT AND DECISION ON REVIEW OF

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P R E F A C E

The Board is publishing this report detailing the reasons for its decision following the review of the performance of the Mobil "M areas" solvent flood in the Pembina Cardium Pool because of both the importance of the particular matter and the widespread interest of the industry. The Board's decision is that this particular solvent flood, for the several reasons discussed in the report, has been and will be considerably less effective as a miscible flood than originally expected. This is regrettable but it is as the Board sees it.

The Board hopes its decision will not be misinterpreted by the industry. It is not condemning all enhanced recovery methods not fully proven and certainly not all solvent floods. The Mobil solvent flood, paraphrasing Mobil's words, was to some extent both technically and economically experimental. Mobil is to be commended for trying it but now that, in the Board's opinion, performance and technical analysis indicate the limited degree to which it has been successful the Board has no choice but to come to the decision it has.

The lack of success of this particular flood has been due to the combined effects of several adverse factors which could not have been fully appraised at the time of the inception of the flood. The results indicate the critical importance in horizontal solvent floods of those factors tending to destroy the continuity of the solvent slug and the necessary continuity of miscibility from displaced to displacing fluid. They suggest that solvent slugs of substantial size are required in horizontal

sweeps under adverse reservoir conditions.

The Board's views on the solvent flood in the M areas should not be taken to apply generally to all horizontal solvent floods and particularly are not at all applicable to vertical solvent floods. Under other reservoir conditions and with somewhat larger solvent slugs, horizontal floods could be entirely successful. Vertical floods, with gravity promoting flow stability, are not subject to many of the pitfalls of horizontal floods and, applied in suitable reservoirs, may be expected to lead to recoveries in the very high percentage range.

The Board asks that, notwithstanding its adverse judgment of a particular solvent flood recognized as partly experimental, industry continue to give full consideration to all new enhanced recovery concepts.

May 4, 1967

I INTRODUCTION

The Proceeding

The subject proceedings were initiated by the Oil and Gas Conservation Board by the publication of notice on July 26, 1966, of a public hearing to hear representations from Mobil Oil Canada, Ltd. and others respecting

(a) the efficacy of the scheme of pressure maintenance conducted under Approval No. 323 in the part of the Pembina Cardium Pool referred to in the approval as areas M-1, M-2, M-3, M-4 and M-5, and

(b) the level of the solvent flood recovery factor modifier for the Pembina Cardium Pool.

Attached Figure 1 is a map of the area subject to Approval No. 323 showing its divisions for the purpose of the scheme.

The hearing was held by the Board from November 22 to November 24, 1966, inclusive.

The Parties

The following had filed submissions and were represented at the hearing:

	Represented by	Abbreviation of Name Used in Report
Mobil Oil Canada, Ltd.	D. W. MacFarlane	Mobil
Imperial Oil Limited	A. G. Winestock	Imperial
Pan American Petroleum Corporation	L. Milne	Pan American
The British American Oil Company Limited	J. Hnatiuk	British American

The Background

The first field tests of miscible flooding with solvent banks in the Pembina Cardium Pool were conducted by Mobil during the period, November, 1957, to December, 1958. The test site was located in the north-west corner of what is now known as area M-1, and the test involved one injection well centred amid four producing wells in a ten acre square unenclosed pattern. The pilot test was designed to assess the effectiveness of the solvent bank driven by separator gas and the influence of water slugs injected late in the stages of the scheme. Also tracer surveys using helium were conducted to determine the nature of the flow profiles and the modification of such profiles due to injection of water slugs. Mobil concluded that the recovery efficiency was in the order of 72 per cent using a solvent slug equivalent in size to about 7 per cent hydrocarbon pore volume.

Mobil on behalf of the unit owners then applied for Board approval of a full scale miscible flood using the method tested in the pilot test but involving a relatively smaller solvent slug. Following hearings, the Board issued Approval No. 271 in October, 1959, approving a scheme for such operations in areas M-1 and M-2 in the North Pembina Cardium Unit No. 1. Six months later Mobil sought approval for the same type of scheme for operations in areas M-3, M-4 and M-5. Thereupon, the Board issued Approval No. 323 in June, 1960, of a scheme for miscible flooding of areas M-1, M-2, M-3, M-4 and M-5 in accordance with Mobil's plans. The location of the areas in the Pembina Field is shown in Figure 1.

At the time these operations were being initiated it was

customary for the Board to hold semi-annual hearings for assigning appropriate maximum permissive rates (MPR's) for pools, wells and projects. At the fall, 1960, hearings on the performance and continuing efficacy of areas M-1 and M-2 became the subject of controversy so considerable that the issues raised were beyond the scope of the MPR hearing. Consequently, the Board called a special hearing on November 16, 1960, to consider the performance and efficacy of the scheme in areas M-1 and M-2 under Approval No. 323. As a result of that hearing, the Board issued a letter to Mobil and to all operators in January 24, 1961, stating the following:

> "The Board has concluded that, while there is some ground for doubt that the scheme will achieve the oil recovery originally anticipated, there is no reason or proper basis at this time for revoking or significantly altering the Board's approval of the scheme. However, it is apparent that much is yet to be learned about the application of the miscible flood process to the Pembina Cardium Pool and that the 41-spot floods in the North Pembina Unit are to some extent experimental, at least at present. Mobil's scheme appears to have been carefully conceived and warrants a fair trial. The Board is not convinced that the viscous fingering phenomenon demonstrated in areal model studies will occur on a comparable scale in the field. From the view-point of conservation the Board is satisfied that the scheme is resulting in pressure maintenance, and that a recovery substantially beyond that obtainable by water flood may result. The Board believes that if later experience should show that the concept or the design of the scheme is faulty, alterations to the scheme could be made before significant underground waste would occur. Nevertheless, the Board has definite reservations regarding the adequacy of the minimum volumes of LPG required for the 41-spots under Approval No. 323.
>
> Accordingly the Board has decided to continue Approval No. 323 but to increase the minimum volumes of LPG to be injected by 20% (an amount consistent with Mobil's original proposal with respect to areas M-1 and M-2)."

Mobil applied in March, 1961, for amendment of Approval No. 323 to permit conversion of areas M-3, M-4 and M-5 to water flood in place of the approved miscible flood. Mobil contended that, until sufficient history was available from M-1 and M-2 to indicate general conformance to the assumptions made in the predictions, these 41-spots had to be considered technically experimental. This situation and uncertainties as to future incremental allowables, investments due to size of slugs, and cost of attempts to control the front to a radial pattern rendered the M-1 and M-2 schemes experimental in an economic sense as well. Mobil stated that there were two key considerations respecting suitability for miscible flooding, namely stratification and injectivity. On this basis, its studies indicated that areas M-3, M-4 and M-5 were inferior to areas M-1 and M-2 for miscible flooding. Mobil nevertheless held to its original estimates that oil recoverable by the miscible flooding of M-3, M-4 and M-5 would be some 25 million barrels more than if the areas were water flooded. The Board denied the application and in its letter to Mobil stated that the reason for denial was "that the requested substitution of water injection for LPG gas injection would lead to waste of recoverable oil."

Mobil therefore proceeded with the scheme as prescribed under Approval No. 323, completing injection of the solvent banks in areas M-1 and M-2 by 1961 and in areas M-3, M-4 and M-5 by 1963. Following injection of the solvent banks, gas had been injected more or less continuously as the main driving fluid, with minor interruptions occurring when relatively small water slugs were injected.

In the spring of 1963 the Board decided that it should set out explicitly the criteria for determining eligibility for enhanced recovery MPR status of miscible floods in the Pembina Cardium Pool. On May 16, 1963, the Board issued a letter to all operators entitled, "Miscible Flood Criteria", stating the following:

> "For the purpose of establishing the eligibility of a scheme in the Pembina Cardium Pool for miscible flood project MPR status, the Board has adopted the criteria stated herein.
>
> An injection scheme designed, approved and operated as a miscible flood may qualify for the miscible flood MPR level upon achieving the following:
>
> (1) Reservoir fluid replacement shall be on a full and continuing basis for a minimum of three consecutive months. Replacement shall be effected at the withdrawal level approximately equivalent to the subsisting allowable for the project.
>
> (2) Reservoir pressure maintenance shall be achieved on a full and continuing basis and in such a manner as to assure that the miscibility between displaced and displacing fluids is maintained.
>
> (3) In general there shall be an overall indication from performance that the flood is effective as a miscible flood on a continuing basis."

In June, 1966, Mobil applied for approval of the conversion of all of the M areas to injection of alternate slugs of water and gas on a continuing basis so that the reservoir volumes of water injected would be slightly in excess of those of the gas injected. Imperial intervened at the hearing, contending that the schemes were no longer functioning as miscible floods and that the question of continuing efficacy of the schemes should be reviewed. The Board did not accept Imperial's intervention in connection

with the hearing of Mobil's application but, in response to Imperial's position, undertook to call a later hearing for the purpose of reviewing the continuing efficacy of the flood in the M areas and the solvent flood recovery factor modifier for the Pembina Cardium Pool. In the meantime the Board granted qualified approval of Mobil's application, permitting injection of alternate slugs of water and gas in the M areas where the total volume at reservoir conditions of all water slugs would not exceed the gas injected. The Board revised and consolidated the then existing Approval No. 323 and issued in its place Approval No. 877.

Pursuant to its notice of hearing dated July 26, 1966, the Board received submissions from Mobil, Imperial, British American and Pan American. In its primary submission, Mobil referred to the Board's May, 1963, letter concerning criteria for miscible floods as the basic terms of reference respecting continuing eligibility. At the hearing Imperial made a submission regarding the general principles to be followed in setting Recovery Factor Modifiers for miscible floods. The Board accepted this as being within the terms of reference of the hearing.

In view of certain technical matters raised in the submissions the Board staff had recommended to the Board that it obtain the advice of a technical expert, more familiar than the staff with certain theoretical aspects of the subject. The Board engaged Dr. L. L. Handy, head of the Petroleum Engineering Department at the University of Southern California, for this purpose. Dr. Handy participated with the Board staff in the hearing and subsequently acted as consultant to the staff and the Board respecting certain technical matters raised.

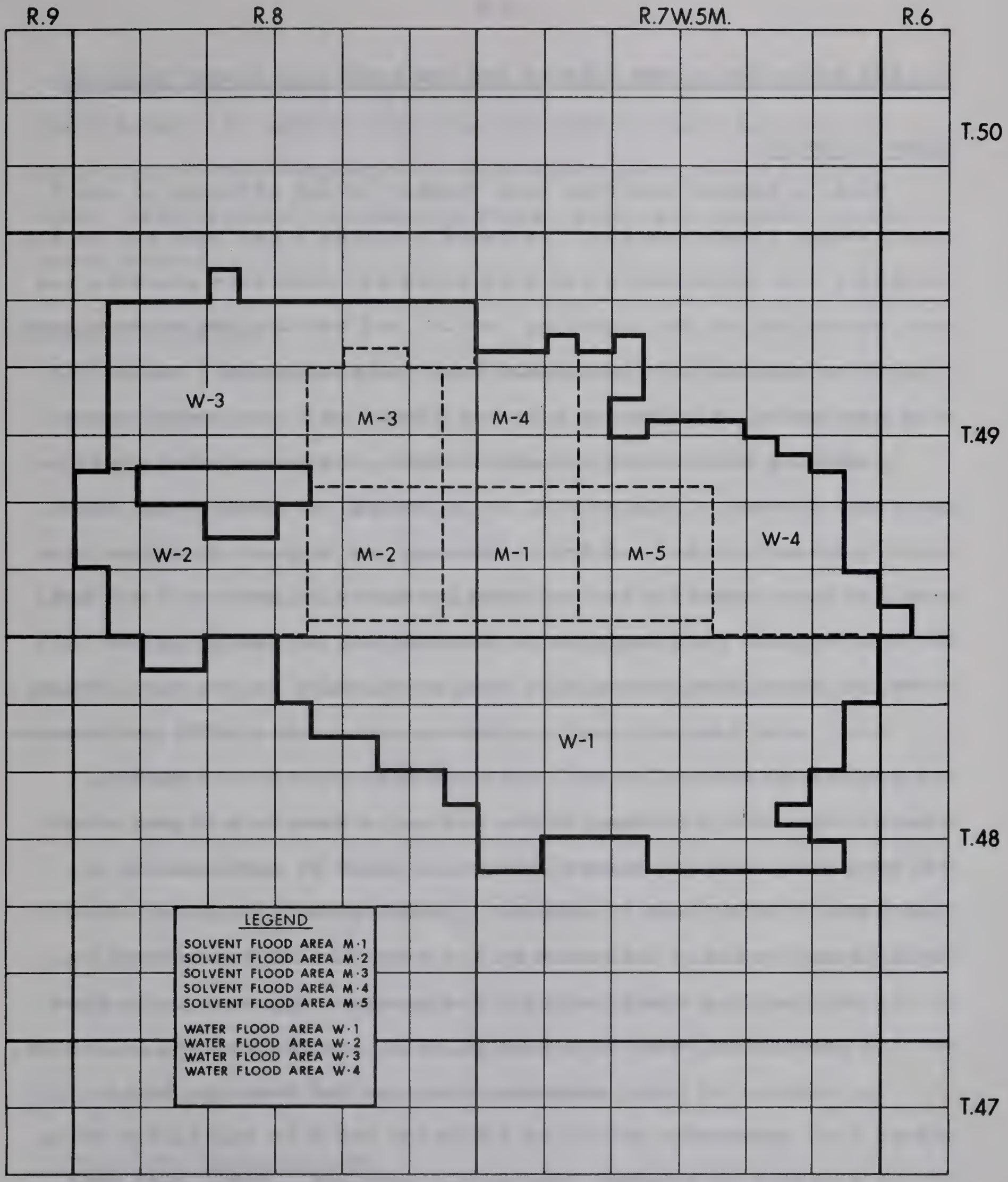

FIGURE - 1

LOCATION OF M AREAS WITHIN APPROVAL No. 323
IN THE PEMBINA FIELD

OIL AND GAS CONSERVATION BOARD
MAY, 1967

II THE POSITIONS OF THE PARTIES AND THE TECHNICAL ISSUES INVOLVED

Views of Mobil

Mobil's general position with respect to the efficacy of the M area solvent floods was that the Board's criteria had been met in all respects; i.e. withdrawals had been replaced, reservoir pressure had been maintained at the necessary levels, and because the schemes were performing generally in accordance with the predictions, the floods were performing as effective miscible floods on a continuing basis.

Comparing performance and predictions, Mobil contended that the monitored arrival of the solvent is following the predictions quite well in areas M-1, M-2 and M-5. Although the arrival of the solvent bank has been generally earlier than predicted in areas M-3 and M-4, Mobil attributes this variance to permeability variation in the reservoir being more severe than that represented in its calculations.

Mobil also took the position that gas-oil ratio (GOR) performance was conforming reasonably well with the predictions. It agreed, however, that GOR's of many of the R-5 wells were much higher than had been predicted but argued that these could be explained by a "gas bubble" effect and by somewhat greater permeability variation in the reservoir than indicated by its mathematical representation of the permeability distribution. The attached Figure 2 taken from Mobil's submission shows each ring of wells from R-1 to R-5 inclusive.

In response to other representations at the hearing, Mobil argued that transverse molecular diffusion would be negligible owing to the presence of numerous impermeable barriers. Mobil also took the position that evidence from solvent flood operations in fields

other than Pembina was not relevant to a review of the efficacy of the M areas. It pointed out, however, what it considered to be deficiencies and ambiguities in interpreting the results of the other field evidence obtained at Parks, Bisti and Chandler in the United States.

Views of Imperial

Imperial contended that the solvent banks in the M areas have been dissipated and miscibility has been lost. It believed that failure of the process was caused primarily by viscous fingering causing the process to degenerate to an ordinary immiscible gas drive at a very early stage. It believed this view was supported by the actual GOR performance. Imperial stated further that, even if viscous fingering and GOR performance were ignored, its calculations show quantitatively that miscibility "has already been destroyed" due to the effect of transverse molecular diffusion.

Imperial reiterated its claim that properly scaled laboratory flow models can be used to predict field performance. It said that recent publications of highly controlled studies, both in the field (Chandler) and in the laboratory, confirmed its original claim that small solvent banks would be destroyed very early due to the effects of viscous fingering. Imperial cited field tests at Bisti, New Mexico, and Parks, Texas, as confirmation of the low recovery efficiency using small solvent bank processes.

Views of British American

British American contended that areas M-1 to M-5 are no longer miscible and presented evidence to show that, due to longitudinal

mass transfer effects, the solvent bank would have been dissipated shortly after its injection. It contended that actual GOR performance in the M areas confirms that the process is performing not as predicted but rather in the manner of an ordinary gas flood. Exceptions to this are those areas being affected by water flood.

Views of Pan American

Pan American submitted an intervention refuting Imperial's arguments and contending that small solvent banks will be successful in the Pembina Cardium Pool and therefore will yield recoveries consistent with the predictions made for the processes. Pan American questioned the validity of Imperial's calculations of the effects of transverse molecular diffusion. It took the position that Imperial's representation of permeability layers could have an important bearing on the results and since Imperial had not actually studied the reservoir preparatory to establishing its layer selection, that the results may not be meaningful. Pan American furthermore submitted that the numerous thin shale barriers spread throughout the reservoir sand would reduce transverse molecular diffusion to a negligible level and that this had not been properly accounted for by Imperial.

Pan American accepted the fact that viscous fingering is potentially damaging to solvent flooding but it maintained that the discreet use of water slugs in the process will minimize fingering.

The Technical Issues Involved

In reviewing the general positions taken by each of the parties, the Board recognizes that there are a number of relatively distinct technical issues involved. The positions of the parties result from

their different views on most of these issues. The principal issues with respect to the M areas seem to be:

1. Reservoir Fluid Replacement - the question of whether or not or to what extent withdrawals of reservoir fluids have been replaced,

2. Reservoir Pressure Maintenance - the question of whether or not or to what extent reservoir pressure has been maintained at an adequate level,

3. Permeability Distribution - the questions of the adequacy of the permeability data and the mathematical representation of the permeability distribution,

4. Impermeable Barriers - the question of the number, continuity and effectiveness of the "impermeable" shale laminae and the shale and ironstone bands,

5. Viscous Fingering - the question of whether or not and if so to what extent viscous fingering will occur under the actual field conditions,

6. Transverse Molecular Diffusion - the question of the extent of transverse molecular diffusion to and from the solvent slugs and its effect on the slugs and the miscibility of the process,

7. Transverse Flow Induced by Pressure Gradients - the question of the extent of pressure gradient induced transverse flow to and from the solvent slugs and its effect on the slugs and the miscibility of the process,

8. Longitudinal Molecular Dispersion - the question of the extent of longitudinal molecular dispersion to and from the solvent slugs and its effect on the slugs and the miscibility of the

process,

9. Accumulation of Free Gas as an Explanation of High GOR's - the question of whether or not it is reasonable to expect that there would be an accumulation of free gas ahead of the solvent slugs and whether this would explain any higher than predicted GOR's in the peripheral wells,

10. Monitoring the Arrival of the Solvent Slugs - the question of whether, and if so to what accuracy, the field data and its interpretation permits determining the actual time of arrival of the solvent slug at various producing wells.

The first two of the issues, on which there was substantial agreement, are the same as the first two performance criteria used by the Board (see page 5). The other issues all have a bearing on the Board's third performance criterion - namely whether actual performance confirms that the reservoir displacement process is miscible. Details of the views of the parties and of the Board on the first two issues are given in Section XI. The other more controversial issues are dealt with individually in Sections III to X and in their total effect, in Section XI.

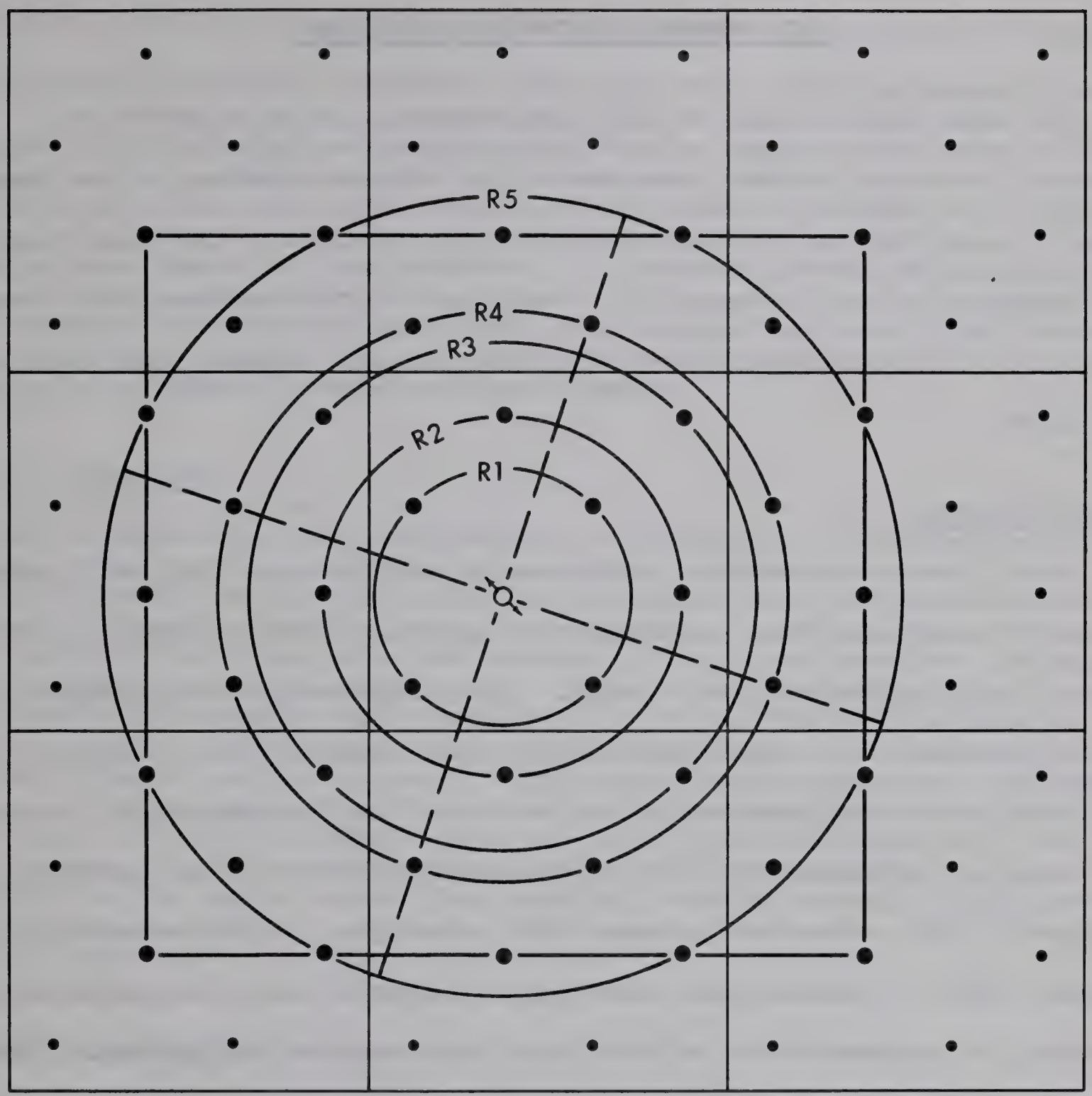

FIGURE - 2

41 SPOT PATTERN

REPRODUCED FROM SUBMISSION OF
MOBIL OIL CANADA LTD.

INJECTION WELL

OIL AND GAS CONSERVATION BOARD
MAY, 1967

III PERMEABILITY DISTRIBUTION

To make predictions of the performance expected under an enhanced recovery scheme a mathematical representation of the permeability distribution of the reservoir is required. The questions of the adequacy of the permeability data and of the mathematical representation of the permeability distribution are issues that must be evaluated.

Views of Mobil

Mobil made theoretical performance predictions for each quadrant of each M area and then combined the quadrant predictions to obtain a total prediction for the M area. The mathematical representation of the permeability distribution for each quadrant was based on the available core analyses which was divided into permeability brackets. The range of permeability in the brackets differed from quadrant to quadrant. This occurred because the selection of the permeability brackets for a quadrant was made on a judgment basis which permitted grouping of permeability values from core samples to minimize the permeability variation in any single bracket. The result was that the representation for some quadrants may contain as few as eight brackets, but for others it may contain as many as twelve.

Mobil stated that the permeability distributions in the reservoir in areas M-3 and M-4 could be more severe than was represented in Mobil's calculations, and it expressed the opinion that the permeability distribution in these areas actually could be similar to that of areas M-1, M-2 and M-5.

Mobil indicated that its method of representing permeability layers in the reservoir likely is in error to a certain extent since the capacity distribution curve is in fact a continuous function and a breakup of this curve into strata "in itself is an obvious violation of the actual facts of the reservoir." However, Mobil maintained that its representation was adequate for the purpose of predicting recoveries and the general nature of performance.

Views of Imperial

The mathematical representations of permeability distributions used by Imperial in its diffusion calculations were patterned after those used by Mobil for the SSE quadrant of M-1 and the NNW quadrant of M-2 and that used by the Board staff in its 1963 MPR submission. Imperial grouped certain layers to obtain a representation containing 6 distinct layers and constituting in each representation 13.2 feet of reservoir thickness which included all layers having significant permeability.

Views of Pan American

Pan American questioned the validity of Imperial's mathematical representation for calculating the effects of transverse diffusion. Pan American contended that Imperial should have studied the actual reservoir data to determine the appropriate layers as they actually occurred. Although Pan American was uncertain as to the number of layers required to represent the reservoir, it emphasized the importance of accurate representation of the actual reservoir layers for the purpose of determining transverse diffusion effects.

Views of the Board

The Board, after comparing the permeability capacity distribution curves used by Mobil with those prepared by the Board staff, believes that Mobil's representation of the variation in permeability for each quadrant is reasonable having regard for the data available. However, the Board suspects, as does Mobil, that core sampling density is inadequate to establish truly representative capacity distribution curves.

The Board is of the opinion that, assuming an intact solvent slug, Mobil's mathematical representation of the reservoir would give a satisfactory prediction of the overall recovery and the general level of performance. However, the representation could be entirely inappropriate for use in calculations where physical similarity with the reservoir is crucial such as the transverse molecular diffusion calculations.

IV IMPERMEABLE BARRIERS

The Cardium formation at Pembina is a complex of conglomerate, porous sands, shale laminae, and shale and ironstone bands. The extent to which the shale laminae and the shale and ironstone bands are effective in restricting the transverse flow of fluids between adjacent permeable layers is one of the issues that must be evaluated. This involves both the vertical permeability and the number and lateral continuity of the laminae and the bands.

Views of Mobil

Mobil divided the reservoir into conglomerate, upper sand, middle sand and lower sand units and described them as follows. The conglomerate unit contains concretionary ironstone and bands of shale. The upper sand unit consists of paper-thin bands of dark grey shale between fine irregular laminae of sand. Bands of concretionary ironstone and shale are also common in this unit. The graditional contact between the upper and middle sand units is marked by a gradual increase in the number and thickness of the shale bands, whereas the gradational contact between the middle and lower sand units is marked by an increase in the number and thickness of sandstone bands. Mobil took the position that the shale laminae and the shale and ironstone bands were completely impermeable and that wherever they were continuous they would be completely effective in preventing transverse flow of fluids.

Mobil did not state how many effective barriers exist, but

claimed that five or six can be readily correlated. It stated that the ironstone bands generally are correlative over extensive areas and that some can be correlated over most of the Pembina Field. It said that shales in the lower and middle sands and the shale between the upper sand and the conglomerate could be correlated across the entire M areas.

Mobil obtained additional evidence on the lateral extent of the barriers from outcrops where some dense layers could readily be followed for the distance of the outcrop. It took the position that the fact that the shales in the upper sand unit are difficult to correlate did not mean that their lateral extent is small. Mobil did agree, however, that some of the impermeable layers extend only a few inches laterally.

At the hearing Mobil was questioned on the effectiveness of the paper-thin laminae with particular attention to vertical permeabilities observed on core analysis. In reply, Mobil stated that the observed vertical permeabilities could be attributed to fractures that develop when the shale dries out, or to swelling of the shale when the core is cleaned with fresh water in the laboratory prior to testing the flow properties of the core. It reaffirmed its contention that the paper-thin laminae are completely impermeable.

Mobil stated that cross-bedding was uncommon in the reservoir and that it would have no effect on transverse flow.

In summary, Mobil contended that the shale laminae and shale and ironstone bands were completely impermeable and sufficiently continuous laterally to be completely effective in preventing

transverse movement of fluid in the reservoir. It maintained that its conclusion is supported by all available core data as well as by observations made in outcrops in the foothills some miles to the west of the field.

Views of Imperial

Imperial observed that some of the shale breaks cannot be correlated and likely are discontinuous. For this reason, Imperial expressed the belief that, however impermeable the laminae or bands may be, there are holes or openings in them which permit the transverse movement of fluids.

Views of Pan American

Pan American stated that shale breaks in the reservoir overlap like shingles and are not continuous over the entire M areas. It presented an analysis of the shale breaks in the M-1 area. Defining the terms "definite break", "shale break" and "shaly", the analysis disclosed the following occurrences:

Average number of definite breaks	9.5
Average number of samples with shale breaks . . .	7.7
Average number of samples indicated as shaly. . .	17.5

Also, Pan American referred to water flood performance in the Pembina Field which shows that breakthrough has occurred earlier than was predicted in many cases. It argued that for this to have taken place transverse flow would have had to be negligible, confirming that the shale breaks are effective barriers to transverse flow.

Board Staff Study

Following the hearing a study was undertaken by the Board staff to determine the degree of effectiveness of the shale laminae and the shale and ironstone bands in restricting transverse flow within the M areas. The study was based on log correlations and the examination of cores and core analyses. The Board staff accepted Mobil's division of the reservoir into the conglomerate, upper sand, middle sand and lower sand units. It made reference to earlier gelogical publications of A. R. Nielsen of Mobil(1) and E. R. Michaelis of Pan American(2).

In its study the Board staff disregarded the middle and lower sand units because they comprise only a minor part of the reservoir. The staff also disregarded vertical fractures. Primary vertical fractures do not appear to be significant on core examinations and secondary fractures that may have been created by well completion techniques cannot be properly evaluated.

The Board staff agrees with Mobil that shale or ironstone bands of thickness more than 1/8 inch or so are impermeable. On the other hand, it does not agree that the paper-thin shale laminae are impermeable. Microscopic examinations of core specimens reveal that sand grains penetrate these thin laminae and vertical permeability measurements indicate that the laminae have permeability in the vertical direction.

---

(1) Nielsen, A. R.: 1957, "Cardium Stratigraphy of the Pembina Field," Alberta Soc. Petroleum Geologists Jour., vol. 5, no. 4.

(2) Michaelis, E. R.: 1957, "Cardium Sedimentation in the Pembina River Area," Alberta Soc. Petroleum Geologists Jour., vol. 5, no. 4.

For the purpose of its study, the Board staff divided the impermeable shale and ironstone bands into two categories, continuous and partially continuous. These are defined as follows:

(1) Continuous barriers are shale and ironstone layers that are correlative from one well to another and therefore probably extend a mile or more. These barriers are taken to be 100 per cent effective.

(2) Partially continuous barriers are shale lenses and layers, ironstone concretions and bands that are not correlative from one well to another and that have lateral dimensions perhaps three or four feet up to approximately one-half mile. Barriers having lateral dimensions of a few inches up to three or four feet are considered completely ineffective and are excluded from consideration. The partially continuous barriers are believed to be about 25 per cent as effective as the continuous barriers.

Description of Reservoir Units

(1) Conglomerate Unit

The conglomerate occurrence is quite irregular and varying in gross thickness from zero to 20 feet, it covers only portions of each of the M areas. Both continuous and partially continuous barriers occur in the conglomerate in the form of a dense shale matrix and concretionary ironstone. These barriers appear to be randomly distributed and vary in thickness from about one inch to about two feet. The number of continuous barriers ranges, in different areas, from none to three or four averaging about one;

while typically 3 or 4 partially continuous barriers are found.

A dense layer commonly occurs between the conglomerate and upper sand units. However, it cannot be correlated across the entire M areas. In some places the conglomerate was deposited directly on the upper sand unit and core analyses substantiate continuous porosity and permeability between these units at some locations. Therefore, the dense layers at the base of the conglomerate is only partially effective in separating the conglomerate unit from the upper sand unit.

(2) Upper Sand Unit

The upper sand unit covers all of the M areas. The unit varies in gross thickness from 10 to 35 feet and from one M area to another. It contains both continuous and partially continuous barriers of shale and ironstone concretions that occur as irregularly shaped overlapping wavy bands. Like those in the conglomerate, these barriers vary in thickness from about one inch to about two feet. Within each M area gaps exist in the barriers due to their limited lateral extent and overlapping nature.

Only one continuous barrier can be correlated over the entire M areas and it lies between the upper and middle sand units. In portions of the M areas up to six continuous barriers are encountered with an average of about two.

Partially continuous barriers - shale lenses, shale layers and ironstone concretions - occur in irregular shapes, sizes and oblique positions. It is not possible to obtain a truly meaningful count of these barriers although on average there would be eight or so.

Views of the Board

In view of the studies of its staff the Board cannot accept the views of Mobil and Pan American that the shale and ironstone bands would be completely effective in preventing transverse flow of fluids between adjacent permeable layers. To determine the extent to which the continous and partially continuous shale and ironstone bands are effective one has to have in mind how many truly continuous and impermeable bands would be required in the combined section of conglomerate and upper sand before transverse flow could be completely disregarded. Even this cannot be determined precisely. Bearing in mind what would seem reasonable in this respect, however, and having regard to the numbers of continuous and partially continuous barriers encountered in a typical section, it would seem to the Board that the actual bands in total might be something like 40 to 60 per cent effective in eliminating transverse flow.

The Board concludes that while it is impossible to determine the effective shielding of the shale and ironstone barriers to transverse fluid movement with precision, the shielding is probably no more than 60 per cent effective. This means that transverse flow by molecular diffusion or under the action of pressure gradients might be expected to proceed at something like 40 per cent of what it would in the absence of the shielding.

V VISCOUS FINGERING

The process of miscible displacement of crude oil has been studied extensively in laboratory experiments. As a means of making quantitative predictions applicable in the field, laboratory flow models have been scaled to relate viscous, gravitational and diffusional forces. When the mobility ratio is unfavourable, viscous fingering has been shown in laboratory models to have a dominant influence on the nature of performance and ultimate recovery obtained. The issue to be considered is whether, and if so to what extent, viscous fingering has influenced the performance and what effect it will have on ultimate recovery from the M areas. Also, the applicability of scaled laboratory flow models to the quantitative prediction of performance in the field is a related issue.

Views of Imperial

Imperial reiterated the position it had taken at previous hearings, namely that unless somehow suppressed visous fingering will have an important destructive effect on any miscible displacement process in which the viscosity of the displacing fluid is less than the viscosity of the displaced fluid. Imperial contended that the performance in the M areas bears out the conclusions it had reached previously from laboratory flow models which showed very rapid dissipation of small solvent bank floods due to viscous fingering.

Imperial further contended that the recent publication(3) of

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(3) Greenkorn, R. A., Johnson, C. R. and Haring, R. E.: "Miscible Displacement in a Controlled Natural System," Jour. Pet. Tech. (Nov., 1965), 1329.

the results of highly controlled miscible displacement tests in the Chandler Field, Oklahoma, and the related laboratory model tests confirms that the laboratory flow models may be used quantitatively to predict field performance.

The Chandler Field experiment involved three tests on a confined five-spot 50 feet square with miscible displacements at unity, favourable, and unfavourable mobility ratios. These tests, plus associated laboratory experiments on confined five spots 22.3 to 44.5 inches square, were designed to measure miscible displacement performance in a controlled natural system and, using known scaling criteria, to develop an approach to modelling the heterogeneous field system. The authors concluded that displacement efficiency in the field is a pronounced function of mobility ratio, thus confirming that the fingering observed in laboratory models occurs in the field. They also concluded that field displacements may be quantitatively predicted by scaled laboratory models if the degree and location of field permeability variations are preserved in the models. Further they stated that arbitrary simplifications of heterogeneity will not necessarily lead to correct predictions of displacement efficiency and, the simpler the model, the more optimistic the prediction.

The authors stated that the concepts that fingering is only a laboratory phenomenon, that diffusion wipes out fingers over the greater distances present in the field, and that miscible displacement in the field should therefore be more efficient than indicated by laboratory models, are not supported by the Chandler experiment.

Views of British American

British American stated the belief that any system in which the viscosity ratio is unfavourable will be inherently unstable. British American said that viscous fingering is an important phenomenon leading to the breakdown of the small solvent banks in the M areas.

Views of Pan American

Pan American stated that it recognized that fingering is a potential problem in solvent flooding and that it had directed much effort toward solving the problem. The appropriate use of water slugs in solvent floods in Pembina would, in its opinion, tend to minimize the effects of fingering.

Views of Mobil

Concerning the evidence from the Chandler Field test and the laboratory model results relating to it, Mobil disagreed with the conclusion that the results indicate that viscous fingering in the field test was accurately scaled from the model. In particular, it questioned the suitability of the non-Newtonian fluids used in conducting the tests as a means of observing viscous fingering. Further, it considered the accuracy of 20 per cent, more or less, obtained in scale-up from laboratory models to the field system to be inadequate considering the relatively small degree of scale-up. It questioned the ability of the authors to scale sand heterogeneities and suggested that the interpretation of the experiment was perhaps better described as a trial and error fit which accommodated differences in heterogeneity between model and field than as confirmation of the scaling of viscous fingering.

Mobil did not present direct evidence at the hearing concerning the question of viscous fingering. At previous hearings, however, it had always taken the position that viscous fingering is primarily a phenomenon of laboratory flow models and will not occur on the same scale in actual field systems. Thus, although Mobil accepts the idea that the miscible flood front will become non-radial and irregular in the field system due to broad areal variations in reservoir properties, it does not agree that the fingers observed in laboratory flow models usually performed on homogeneous sand packs will occur proportionally in field systems.

Views of the Board

The Board has given detailed consideration to the views of the participants at the hearing and also has reviewed the recent technical literature relating to viscous fingering. The Board is satisfied that, where there is an adverse viscosity ratio between displaced and displacing fluid, the flow system is potentially unstable and viscous fingers will develop unless somehow suppressed. In the M areas solvent flood the viscosity ratio between oil and solvent is about thirty to one and the viscosity ratio between solvent and driving gas is two to one. These conditions are conducive to viscous fingering.

Transverse flow due to molecular diffusion and pressure gradients, discussed in Sections VI and VII, will tend to reduce the fingering but at the expense of the solvent slug itself. In the M areas the influence of molecular diffusion in reducing fingering is likely small in view of the relatively high flood

rate of some three feet per day from the injector to the R-2 ring. The injection of water slugs behind the driving gas, although tending to reduce fingering probably would do so only to a limited extent. Logitudinal dispersion, discussed in Section VII, can result in a graduated concentration and viscosity profile between the solvent and the oil and thereby reduce fingering, but in the present case the solvent slug size is such that the solvent bank would likely be largely dissipated before this could be effective.

With respect to the Chandler Field test and the related laboratory model test, the Board is not able to determine whether the results prove that laboratory model tests may be used for quantitative predictions of field performance but, in the Board's opinion, the tests do confirm the importance of viscous fingering in field applications.

In its letter dated January 24, 1961, the Board indicated that, on the basis of information it then had before it, it was not convinced that the viscous fingering phenomenon demonstrated in the model studies would occur on a comparable scale in the field. The Board still is unable to draw firm conclusions concerning the severity of viscous fingering in the field but it is now further convinced of the seriousness of viscous fingering in the M area floods and believes that, in the lack of factors which would be effective in eliminating the fingers, the probability is high that fingers have developed with resulting serious deterioration of the solvent bank.

VI TRANSVERSE MOLECULAR DIFFUSION

Because of the variation in permeability the solvent bank will be more advanced in some permeability layers than others. This means that the solvent bank in a given permeability layer may be in lateral contact with oil in an adjoining layer of lower permeability, whereas in an adjoining layer of higher permeability it may be in lateral contact with injected gas. Under these conditions the possible dissipation of the solvent bank by the diluting effects of transverse molecular diffusion of solvent into oil (and vice versa) and solvent into driving gas (and vice versa) requires appraisal.

Views of Imperial

Imperial pointed out that in the Pembina Cardium system, where different rates of displacement occurred in each permeability layer, the solvent bank will be exposed to molecular diffusion transverse to the direction of flow causing dilution of the solvent bank to a level below that required for miscibility. It submitted calculations for a six layer system using the permeability distribution proposed by Mobil for the SSE quadrant of M-1 and the NNW quadrant of M-2 and as employed by the Board staff in its 1963 MPR submission. Imperial employed the calculation method presented by Koonce and Blackwell(4).

Imperial used simultaneous counter molecular diffusion coefficients of 0.11 square feet per day between gas and solvent and

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(4) Koonce, K. T. and Blackwell, Robert J.: "Idealized Behaviour of Solvent Banks in Stratified Reservoirs," Soc. Pet. Eng. Jour. (Dec., 1965), 318.

0.011 square feet per day between solvent and oil. These values were divided by five to account for tortuosity and then reduced by a further arbitrary 80 per cent to account for shielding due to the shale barriers between permeability layers. For the models patterned after Mobil's data Imperial accepted the solvent bank distribution presented in Mobil's submission of May 20, 1966. For the model patterned after Board staff data, Imperial assumed a 2 per cent solvent bank. Imperial calculated for all three models that, after a total injection of about 5 per cent hydrocarbon pore volume, requiring five years, the solvent concentration in all layers would be below that required for miscible displacement. On the basis that the calculations reasonably approximate reservoir conditions in the M areas, Imperial concluded that miscibility would have been destroyed in all M areas at this time even if transverse molecular diffusion were the only cause for dilution of the banks. Imperial further pointed out that calculations show that to maintain solvent banks for 10 years shielding in excess of 95 per cent would be required.

At the hearing Imperial stated that the calculations show that, if the diffusion coefficient between gas and solvent were reduced to 0.011 square feet per day and applying the same factors of 5 and 80 per cent to account for tortuosity and shielding, it would take 10 years to lower the concentration of the solvent bank everywhere below the level required for miscibility.

Views of Mobil

Mobil stated that, on the basis of its lithological examinations, it considered the conditions for transverse diffusion

between strata to be very unfavourable. As discussed earlier, in Mobil's expressed opinion, the shale and ironstone layers provide completely effective shielding between adjacent permeability layers. Imperial's calculations of potential transverse diffusion effects are, according to Mobil, not at all representative of actual conditions since Imperial assumes only 80 per cent shielding and employs a gas-solvent diffusion coefficient several orders of magnitude too large. Though it considered the subject academic, Mobil expressed the belief that Imperial erred by using a diffusion coefficient for gas-solvent based on calculations applicable to a gas to gas system whereas it should have employed a value representing the gas to liquid system existing in the reservoir.

Views of Pan American

As referred to in Section IV, Pan American maintained that wells in the M areas showed an average of 9.5 definite shale breaks plus an additional 17 sections being shaly. It maintained that there appear to be twenty to thirty shale breaks and that these shale breaks would reduce transverse diffusion effects "to an extremely low level."

Pan American also questioned the validity of the six layer system used by Imperial for diffusion calculation purposes. It emphasized the importance of the layering assumed for the diffusion calculations being representative in a physical sense of the situation in the reservoir. It pointed out that the more layers used in the calculation, the greater would be the calculated effect of diffusion.

Views of the Board

The Board agrees with Pan American that, for the diffusion calculations to be fully meaningful, the permeability layering which is assumed must be physically representative of that in the reservoir. Moreover the degree of shielding assumed and the values of the diffusion coefficients used are also of critical importance in the calculation.

The Board does not believe that Imperial's permeability layering is likely to be suitable for the diffusion calculations and suspects that it results in exaggerating the effect of diffusion. On the other hand the Board doubts if the shielding would be so effective as the 80 per cent assumed by Imperial. The Board believes the solvent-gas diffusion coefficient used by Imperial is too high.

Imperial's calculation technique was not questioned at the hearing and the Board is not in a position to assess it.

The Board's overall assessment of the transverse diffusion matter is that Imperial has demonstrated that if the solvent bank were otherwise intact there is a serious danger that it could be dissipated by transverse molecular diffusion. However, the Board believes that transverse flow under the action of pressure gradients would be a more serious danger to the solvent bank. This is discussed in the next section.

VII TRANSVERSE FLOW INDUCED BY PRESSURE GRADIENTS

The variation in permeability which results in the solvent bank being more advanced in some permeability layers than in others, coupled with the partial shielding, causes the development of pressure gradients transverse to the direction of flow. These transverse gradients arise from the fact that the pressure gradient in the driving gas behind the solvent slug is lower than that in the oil ahead of it with the result that at any radial distance from the injection well the pressure in a high permeability layer will tend to exceed that in an adjoining lower permeability layer. Given complete shielding the gradient across the barrier may be large but no transverse flow will occur. Given partially effective shielding intermediate gradients will develop and these will cause transverse flow through the breaks in the barriers. The issue, like that for transverse molecular diffusion, is the extent of such flow and whether it would result in the breakdown of the solvent slugs.

Views of the Operators

The possibility of transverse flow induced by pressure gradients in the M areas was not discussed in a direct way by any of the participants in the hearing. In its intervention to Imperial's submission, Pan American in effect stated that the performance of the Pembina water floods confirms that transverse flow is not occurring and that it can be inferred that impermeable barriers have reduced any such effect to a very low level. Similarly, Mobil argued that no transverse flow could occur

because of the innumerable competent shale barriers and the absence of any cross bedding.

Views of the Board

The Board is unable to assess the impact of transverse flow caused by pressure gradients in any quantitative way. It does recognize, however, that such transverse flow would take place and, having regard for the probable pressure gradients, that its effects would likely be much more serious than that of molecular diffusion. In view of the Board's conclusion in Section IV that impermeable barriers are no more than 60 per cent effective, the Board is satisfied that transverse flow has in all probability caused a serious dissipation of the solvent banks.

VIII LONGITUDINAL DISPERSION

As a solvent bank progresses through a permeability layer it is in contact with reservoir oil at its leading face and driving gas at its trailing face. Assuming miscibility, no interfaces exist. Longitudinal dispersion of solvent into oil (and vice versa) and solvent into gas (and vice versa) takes place with the result that the initially very steep concentration gradients become increasingly diffuse. The accompanying change of the abrupt viscosity profile to a gradual one acts to reduce the development of viscous fingers. The issue, however, is whether the solvent bank is large enough so that continuous miscibility will still be maintained from the oil through to the driving gas notwithstanding the diluting effects caused by the dispersion.

Views of British American

British American submitted results of calculations based upon Price and Donohue[5] purporting to show the effectiveness of various sizes of slugs in improving recovery where the fluid systems, pressure, temperature, rate of injection, and other conditions were similar to those of the M areas. In the Board's examination of the method it noted that it assumes a homogeneous reservoir with no viscous fingering. Since the homogeneous reservoir is equivalent to a single permeability layer, the method does not deal with cases where transverse flow by molecular diffusion, or under the action of pressure gradients, may take place.

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(5) Price, H. S. and Donohue, D. A. T.: "Isothermal Displacement Processes with Interphase Mass Transfer," Paper Number SPE 1533, presented at the 1966 Fall Meeting of AIME, Dallas, Texas.

It assumes that "the reservoir fluids are in thermodynamic equilibrium at all times." The equilibrium is reflected in the calculations by "equilibrium ratios" applicable to the distribution of individual components between two phases. Initially, however, the fluid system in the M areas would not involve two phases. Nonetheless, British American expressed the view that its calculation, based upon the Price and Donohue method, is applicable to the effect of dispersion on the solvent slug. It stated that "there is inevitably numerical dispersion to some degree associated with calculations of this type"; and, while no attempt was made to scale the numerical dispersion to what actually occurs in the reservoir, it was of the opinion that the mechanisms operative in the reservoir "would tend to initiate the same type of behaviour."

British American's calculations showed recoveries of 35.7 per cent with no solvent slug (i.e. lean gas drive), 39.4 per cent with a 2 per cent hydrocarbon pore volume solvent slug, and 59.8 per cent with a 10 per cent hydrocarbon pore volume solvent slug. It therefore expressed the conclusion that, due to the influence of longitudinal dispersion, the one per cent slug used in each M area would be destroyed shortly after the driving gas phase is injected. Due to the fact that in its calculations the driving gas is shown to penetrate the small solvent bank rapidly, it predicted that the producing wells would show early increases in gas-oil ratio due to lean gas breakthrough followed somewhat later by entry of enriched gas (solvent slug deteriorated to a gaseous phase).

Views of Mobil

Mobil argued that, since British American's calculations apply to the case of a gas driving an immiscible liquid, they are not relevant to the Pembina miscible system.

Views of the Board

The Board agrees with Mobil that the British American calculations are not applicable to the Pembina miscible system but rather to situations in which there is rapid dispersion leading to an equilibrium distribution of components between separate phases. As the Board sees it, these calculations are unrelated to the question of whether or not the solvent slugs used in the M areas were of adequate size.

The Board recognizes the importance of longitudinal dispersion - both its possible beneficial effect in reducing the fingering tendency, and the potential danger from it in dissipating the solvent slug. The Board suspects that the effects of longitudinal dispersion on the 1.2 per cent of hydrocarbon pore volume solvent slugs would be adverse rather than beneficial but this is not in the Board's opinion proven by British American's calculations.

IX ACCUMULATION OF FREE GAS AS AN EXPLANATION OF HIGH GAS-OIL RATIOS

The producing GOR's of many of the wells in the R-5 ring have been significantly higher than had been predicted by Mobil. The issue to be considered is whether or not it is reasonable to expect that there would be an accumulation of free gas ahead of the solvent slugs and whether this would explain any higher than predicted GOR's in the R-5 wells.

Views of Mobil

Mobil contended that the higher than predicted producing gas-oil ratios of the R-5 wells resulted from the pressure depletion prior to commencement of pressure maintenance operations. Gas released from solution in the crude oil was displaced towards the edges of the patterns and accumulated in regions where wells were shut in. As a result, the GOR at most R-5 wells would be higher than predicted. Mobil stated there was a free gas saturation in all of the M areas at the commencement of injection operations and that in areas M-3 and M-4 it was higher than in the other M areas because of a greater degree of pressure depletion before injection began. During the hearing this phenomenon was referred to as the "gas bubble" effect.

Mobil submitted that earlier in the life of the schemes it was possible to distinguish between free solution gas and injected gas but now that the solvent bank in the most permeable layers is approaching or has reached the R-5 wells, this is not possible. Mobil stated that it had not prepared a quantitative estimate of the gas saturation at the start of the flood, but it suggested

that pre-flood gas saturation was sufficiently high to account for the observed performance even where the GOR's reached as high as 14,000 cubic feet per barrel.

Mobil agreed that the gas bubble theory is important to its interpretation of the performance. It acknowledged that, if this theory were invalid, then the high GOR's experienced ahead of the interpreted solvent bank front would constitute direct evidence that the gas has broken through ahead of the solvent bank. Mobil further agreed that this would indicate that the process was no longer a miscible one.

Views of Imperial

Imperial claimed that Mobil, in an attempt to refute Imperial's argument that the R-5 wells' performances are poorer than predicted, had resurrected its completely unique and, in Imperial's opinion, completely unfounded gas bubble theory.

Views of the Board

The Board notes that the GOR performance of the R-5 wells in areas M-1, M-2 and M-4 is similar and generally shows a gentle climb during the first four years after commencement of the scheme in each area. The increase in GOR's during this period more or less matches the period during which there was still a slightly declining reservoir pressure in the R-5 regions. During the same period of time, recovery of oil in place from each area was about two per cent. After this time the GOR performance became quite erratic with some R-5 wells exhibiting GOR's as high as 14,000, suggestive of gas breakthrough from some source. A

number of R-5 wells in the M-2 area have exhibited low GOR's which is possibly due to the influence of offset water flood operations. Performance of the R-5 wells in the M-3 area is similar to those in the M-2 area except that the evidence of "gas breakthrough" appears at only one per cent recovery since flood start. The R-5 wells in area M-5 have exhibited widely varying GOR performance ever since the scheme began. This is possibly due in part to the influence of fluid injection in the M-1 area and the offsetting water floods instituted three or four years before commencement of injection in the M-5 area.

(a) Material Balance Consideration

The discussions at the hearing respecting the gas bubble effect focused around the influence the free gas saturation would have on the R-5 wells. The Board believes that this effect, if valid, would also apply to all wells in each area and decided to conduct material balance calculations to determine whether the gas bubble theory is viable having regard for the amounts of free gas available. The amount of gas calculated to be liberated, but not produced, during primary depletion was compared with the amount of gas produced prior to solvent bank arrival as interpreted by Mobil.

To determine the probable range of free gas available, the oil in place was varied to represent, in the opinion of the Board, the maximum and minimum volumes effectively contributing to production. The calculated ranges of free gas available in each M area are tabulated below. The table also shows the total excess gas produced ahead of the solvent bank using Mobil's interpretation

of the solvent bank position.

Area	Range of Free Gas Available Bscf	Excess Gas Produced Bscf
M-1	0.79 to 2.00	1.08
M-2	1.25 to 3.22	0.98
M-3	1.76 to 3.67	0.54
M-4	2.14 to 4.33	0.91
M-5	0.72 to 2.27	0.61

On the basis of the material balance calculations, the excess gas produced could be theoretically explained by the free gas available. The results therefore do not deny the possibility of the gas bubble theory, but they cannot offer proof of it.

(b) The Gas Bubble Theory in Light of the Fluid Displacement Concept

A question raised at the hearing was whether the gas bubble effect postulated by Mobil was rational and consistent with established fluid displacement concepts. To examine this question more closely, the Board reviewed the concepts of fluid displacement and two-phase flow which would apply in predicting performance in the M areas. For this purpose the Board adopted the following assumptions which are considered reasonably applicable to the M areas:

(a) The reservoir consists of a number of layers with different permeabilities but each layer in itself is homogeneous.

(b) The free gas saturation was uniform at the start of miscible displacement.

(c) The reservoir pressure does not decrease during displacement.

(d) The solvent bank displaces oil and indigenous free gas in a piston-like manner.

Consider first the case where the layers are separated by impermeable barriers so that no transverse flow between layers can occur. According to the piston displacement assumption the oil and gas ahead of the solvent bank will be completely displaced by the advancing solvent. Furthermore, the ratio of flowing gas and oil immediately ahead of the solvent will be equal to the ratio of the gas and oil saturations in this region. Since gas has a much lower viscosity than oil, one can show that the gas saturation in this region will be only slightly in excess of the minimum gas saturation required for gas flow.

Because of the low gas saturation required for the gas flow, displaced oil will accumulate forming an oil bank downstream from the solvent bank. (An oil bank is defined here as a region in which the oil saturation is higher than that at the start of the flood.) The rate of advance of the leading edge of this oil bank will be substantially greater than the rate of advance of the solvent bank(6). Downstream from the leading edge of the oil bank the gas saturations will be uniform and equal to the initial gas saturation. Furthermore, the flowing gas-oil ratios in the downstream region will be constant and equal to the gas-oil ratios at the time of pressure stabilization. Because the flowing gas-oil ratios in this latter region are the equilibrium ratios for the existing gas saturations, the quantities of gas and oil enter-

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(6) Gatlin, C. and Slobod, R. L.: "The Alcohol Slug Process for Increasing Oil Recovery," Trans. AIME (1960) Vol. 219, 46.

ing and the quantities leaving each volume element are equal. No mechanism exists, therefore, for accumulating either gas to form a gas bank or oil to form a second oil bank further downstream.

For the above model of the displacement process the producing gas-oil ratios will stabilize for full pressure maintenance and remain constant until the oil bank arrives at the producing well. When the oil bank arrives at the producing well gas-oil ratios will decline and remain constant at the lower ratio until arrival of the solvent bank.

Although the preceding model is somewhat idealized the predictions of gas-oil ratio history are entirely logical even for less ideal systems. The advancing solvent bank is completely equivalent to injecting and advancing a bank of oil. The distribution or even composition of fluids behind the solvent front is of no consequence so long as the piston-like displacement assumption is valid. One would not expect to increase producing gas-oil ratios by injecting oil even for a pre-existing gas saturation. The logic is no different for injecting a solvent bank.

The preceding discussion assumes that effective barriers occur between the permeability layers. The Board believes that in the Pembina Cardium reservoir there will be a certain amount of transverse flow between layers which would have the effect of making the system perform more nearly as a single layer. In this instance, the GOR's ahead of the flood bank would tend to stabilize and then decline when the oil bank arrived. The performance to be expected from R-5 wells would therefore be similar to that

described above if the miscible displacement process continued to be fully effective.

It is important to note that, for a fully effective miscible displacement operation with full pressure maintenance, the gas-oil ratios prior to solvent bank arrival would not be expected to exceed those observed at the minimum reservoir pressure. Hence, even in a system where producers remote from the injector tend to stabilize at a pressure level lower than wells near the injection point, those wells should not experience GOR's higher than that reached at the lowest pressure level in their region of the pattern. This means that, if the miscible displacement process has remained effective, the GOR's at the R-5 wells in the M areas should not exceed the GOR levels experienced when the reservoir pressures in those regions were at their lowest level.

On the basis of this review, the Board concludes that Mobil's gas bubble theory is not consistent with established principles and is not acceptable as a means of explaining abnormal high GOR's at R-5 wells. Consequently, the Board must conclude that the high and increasing gas-oil ratios at the R-5 wells are very likely caused by arrival of injected gas.

X MONITORING THE ARRIVAL OF THE SOLVENT BANK

By periodic sampling and analysis of the fluids produced from the wells Mobil endeavoured to detect the arrival of the solvent at various producing wells. Questions of some importance in the assessment of the flood scheme are whether Mobil's monitoring data are reliable and whether Mobil's interpretation of the data is sound. The basic data used to trace the advance of solvent banks in each injection pattern were not available to the Board and the public prior to or during the hearing. Subsequent to the hearing, at the request of the Board, Mobil submitted the results of its solvent bank monitoring to the Board and discussed its method of interpretation with the Board staff.

(a) Mobil's Method of Monitoring the Solvent Bank

Generally speaking, most wells were continuously produced and sampled monthly until the arrival of the solvent bank was suspected. When solvent in significant quantities was detected at a well, the well was shut in and a sample was obtained each month thereafter. Preparatory to sampling, wells were produced and "the sample is taken after the system has become stabilized." The graphs submitted by Mobil indicate that in almost all wells the frequency of sampling has dropped to 0 to 3 samples per year since the first part of 1964.

Propane, normal butane and isobutane contents of the gas were determined by chromatographic analysis of the samples. Using equilibrium ratios the amounts of propane, normal butane and isobutane present in the oil produced were calculated. The total

amount of propane and butanes produced with one stock tank barrel of oil was then determined and presented. The methane content per barrel of stock tank oil was also determined and plotted to indicate the amount of dry gas produced. A background level of 15.2 pounds of indigenous propane and butanes per stock tank barrel of oil was determined from analytical data.

(b) Mobil's Manner of Interpretation of Data

At the meeting held subsequent to the hearing between representatives of Mobil and the Board staff, Mobil stated that it had not been able to devise a method by which the solvent bank arrival could be determined with certainty in all cases. When a significant rise in propane and butanes content above the background level of 15.2 pounds per stock tank barrel of oil was associated with a low producing gas-oil ratio (near the solution gas-oil ratio), Mobil interpreted it as a definite detection of solvent bank arrival. However, when a significant rise in propane and butanes content was associated with a high producing gas-oil ratio (well above the solution gas-oil ratio), Mobil said that the solvent bank arrival could be masked. In this circumstance, the time of arrival was subject to wide variance in interpretation and a knowledge of solvent bank position at other wells was used in estimating the actual arrival time.

Board Staff Interpretation

The Board staff has examined the graphs provided by Mobil depicting for each well the monitored propane and butanes content and has made its own best estimate of solvent bank arrival time.

Since the background level of propane and butanes increases with increasing GOR, the rise in propane and butanes content per stock tank barrel of oil produced above Mobil's reference level of 15.2 is not in itself confirmation of solvent bank arrival. The Board staff estimates the background level of propane and butanes for GOR's of 1000, 2000, 5000 and 10,000 to be around 22, 31, 58 and 103 pounds per stock tank barrel of oil produced respectively. Evidence of solvent bank arrival is only conclusive if the measured propane and butanes content exceeds any possible background level of propane and butanes at the existing GOR.

The comparison between Mobil's interpretation of arrival times and the Board staff interpretation of arrival times may be summarized in the following way. The Board staff interpretation of solvent arrival time is virtually identical to that of Mobil for the bulk of the R-1 and R-2 wells. The interpretation of solvent arrival at the R-3, R-4 and R-5 wells is difficult. In many instances, Mobil interprets an increase in propane and butanes content as indicative of arrival of the solvent bank, whereas the Board staff believes it was indicative of arrival of the injected gas.

Table 1 presents a comparison of the Mobil and the Board staff interpretations of solvent bank arrivals at each concentric ring of producers. While in no case did Mobil indicate an arrival of injection gas ahead of solvent, the Board staff interprets the data in this way in a number of cases, particularly in the R-4 and R-5 rings.

Table 2 presents for each M area the solvent swept region

in the most permeable layer as interpreted by Mobil and by the Board staff, on the basis of information available to September, 1966. The Board staff considers its swept area figures to be a minimum since it assumed that the solvent bank was dispersed before the indicated arrival of injection gas whereas in some cases the solvent bank could have passed by the wells being monitored between sampling periods.

Views of the Board

The Board has reviewed Mobil's method of solvent monitoring and its method of interpretation of solvent bank at producing wells.

The Board believes that to the first part of 1964 the frequency of monitoring was satisfactory but thereafter was not fully adequate.

With respect to the interpretation of solvent bank arrival, Mobil clearly recognized the influence of high gas-oil ratios but it still appears not to have given sufficient weight to the background level of propane and butanes associated with such ratios. The Board believes that in a number of high gas-oil ratio cases Mobil has interpreted a high propane and butanes content as evidence of solvent bank arrival, whereas in fact it was caused by injected gas.

The Board recognizes that because of infrequent monitoring, it is possible that the solvent bank could have passed by some of the wells between sampling periods. It therefore agrees that the Board staff interpretation of the miscibly swept area is a minimum. On the other hand, for the reasons discussed, the Board has

difficulty accepting Mobil's version of the area swept to September, 1966, let alone Mobil's contention that the full area of the patterns will be miscibly swept within the life of the project. The area which has been or will be miscibly swept must lie between the minimum Board staff figures and the area of the patterns. In the Board's judgment, the areas which have been or will be miscibly swept in the most permeable layers are probably not larger than from one quarter to one third the way between the Board staff areas and the pattern areas. This would be equivalent to about three quarters of Mobil's version of the area swept to September, 1966. These figures are also shown in Table 2. In the less permeable layers the areas swept before loss of miscibility may be expected to be even less because of the smaller size of the solvent slugs.

TABLE 1

Number of Wells at Which the Arrival of Solvent or Injected Gas is Indicated on the Basis of Data Available to September, 1966

	R-1 4 wells			R-2 4 wells			R-3 4 wells			R-4 8 wells			R-5 16 wells		
	Mobil	Board Staff		Mobil	Board Staff		Mobil	Board Staff		Mobil	Board Staff		Mobil	Board Staff	
	Solv. Slug	Solv. Slug	Inj. Gas	Solv. Slug	Solv. Slug	Inj. Gas	Solv. Slug	Solv. Slug	Inj. Gas	Solv. Slug	Solv. Slug	Inj. Gas	Solv. Slug	Solv. Slug	Inj. Gas
M-1	4	4	0	4	4	0	4	2	2	6	1	7	6	-	7
M-2	4	4	0	4	2	2	4	3	1	8	3	5	4	-	6
M-3	4	4	0	4	4	0	4	1	2	7	-	6	2	-	7
M-4	4	4	0	4	3	1	3	1	3	6	-	7	1	-	2
M-5	4	4	0	3	3	0	3	2	1	5	2	2	4	-	4

TABLE 2

Miscibly Swept Area in Most Permeable Layer
Interpreted from Monitored Solvent Bank Arrivals
(Data Available to September, 1966)

Area	Solvent Slug Size % HCPV	Total Area of Pattern Acres	Mobil Interpretation of Area Swept to September, 1966 Acres	Board Staff Interpretation of Final Area Swept Acres	Board Judgment of Final Area Swept Acres
M-1	1.22	2,560	2,240	1,010	1,650
M-2	1.65	2,560	2,050	1,050	1,720
M-3	0.82	2,400	1,350	690	1,130
M-4	0.84	2,560	1,580	640	1,050
M-5	1.00	2,560	1,230	840	1,370
Total		12,640	8,450	4,230	6,920

XI DEGREE OF CONFORMANCE WITH BOARD'S CRITERIA

(a) Reservoir Fluid Replacement

Views of Mobil

Mobil submitted that fluid withdrawals in each of the M areas had been more than fully replaced by fluid injection since commencement of the schemes.

Views of Others

The other participants in the hearing did not express opinions respecting replacement of fluid withdrawals in the M areas.

Views of the Board

The Board staff has reviewed the replacement factors for the M areas using its own estimates of fluid volume factors and reservoir pressures and has confirmed that replacement ratios of one or greater have been maintained on a continuing basis in each M area since commencement. The Board accepts Mobil's interpretation as confirmed by the Board staff and therefore concludes that this miscible flood criterion has been satisfied.

(b) Maintenance of Reservoir Pressure

Views of Mobil

Mobil submitted an isobaric map showing for the month of September, 1966, the current levels of reservoir pressure throughout the M areas. It pointed out that the pressure controlling miscibility is the pressure in the back mixing zone (i.e. the mixing zone between the solvent bank and the driving gas), and it

listed the minimum pressures required for complete miscibility for each pattern. Mobil stated that the average reservoir pressure in all patterns exceeds the minimum pressure required to ensure complete miscibility. It conceded, however, that the pressures in two small areas on the east side of pattern M-4 and the northwest corner of pattern M-3 are below that required for full miscibility. Also on the basis of its most recent interpretation of the positions of the solvent banks, as presented at the hearing, it agreed that the back mixing zone was very near the area in the east side of pattern M-4 whose pressure was insufficient to sustain full miscibility.

Views of Others

The other participants in the hearing did not discuss or take issue with Mobil's interpretation of reservoir pressure levels or the minimum pressures required to sustain miscibility.

Views of the Board

The Board agrees substantially with Mobil's interpretation that pressure levels in most of the M areas have been sufficient on a continuing basis to assure complete miscibility between the displaced and displacing fluids. An important aspect of this conclusion is that it assumes no breakdown or serious dilution of the solvent bank. If solvent bank concentration levels in the mixing zone between the driving gas and the solvent were significantly lower than assumed, it would follow that fluids may be immiscible now and could have been immiscible at some previous time. The Board is satisfied, however, that Mobil has taken

reasonable steps to control withdrawals so that pressure levels would be sufficient to maintain miscibility.

(c) Indication of Effectiveness from Overall Performance

One test of the continuing efficacy of the scheme based on performance is to compare the actual and predicted time of arrival of the solvent bank at the producing wells.

Another test is the comparison of actual and predicted GOR performance. In the M areas it is important to consider the expected and actual GOR performance at each ring of producers. After the solvent bank has passed any ring of producers, the gas-oil ratios at that ring must be expected to be higher than the gas-oil ratios at any ring ahead of the solvent bank.

(i) Solvent Bank Arrival Times

Views of Mobil

In its primary submission Mobil presented a table showing for each M area the comparison between predicted and interpreted solvent bank arrival time for all wells. The comparisons were based on a definition that arrival was considered to be on time if it occurred within plus or minus 0.5 per cent of the recovery of the pattern oil in place at which it was predicted. Mobil concluded that patterns M-1, M-2 and M-5 are following the prediction quite well, while M-3 and M-4 have had premature solvent bank arrival at most wells. It attributed the variance between performance and prediction for the M-3 and M-4 areas to the use in its models of a stratification less severe than that which actually exists in the reservoir. Mobil summed up its conclusions by stating

that in total the actual solvent bank arrival was in reasonable agreement with predictions.

Mobil agreed that its method of comparison of actual with predicted arrival times would permit fairly large discrepancies to exist with the arrival still being considered to be "on time".

Views of Others

Other participants in the hearing did not express opinions concerning Mobil's interpretations of solvent bank arrival.

Views of the Board

The Board recognizes that no prediction can be exact and that precise agreement between actual performance and prediction cannot be expected. Furthermore additional uncertainties are introduced in this case because of a deficiency in the frequency of sampling and the difficulties inherent in the interpretation of the monitoring results.

As is stated previously, the Board agrees with Mobil's interpretation of arrival times in the R-1 and R-2 rings of wells. In view of the limitations of the monitoring technique and on the strength of the comparisons between the interpretations shown in Section X, Table 2, the Board recognizes that there is a considerable margin of error in determining the time of arrival of the solvent bank at the majority of the R-3, R-4 and R-5 wells. Notwithstanding this margin of error, it appears to the Board that the monitoring results, rather than confirming the predicted arrivals of solvent at the R-4 and R-5 rings, and in some cases in the R-3 ring, suggest instead that in each case the solvent

bank in the most permeable layer has been largely dissipated. The Board therefore disagrees with Mobil and takes the position that in the majority of wells in the R-3, R-4 and R-5 rings the performance has failed to conform with the predictions and in the most permeable layers is not in accord with continuing miscible displacement.

(ii) GOR Performance

Before comparing the actual and the predicted GOR performance, it is important to clarify the manner in which production was actually taken and the manner in which it was assumed to be taken in the prediction. Actual production was taken more or less as follows. In general, any well experiencing high GOR's was either shut in or produced at a restricted rate and, for any well at which solvent bank arrival had been monitored, the well was shut in to avoid production of the solvent bank. During the early period of injection in each pattern about three quarters of the wells, constituting all but a few wells in the outer rings, were produced continually. Then as the solvent bank advanced outward from the injector, the inner ring wells were shut in. Thus, the number of wells producing was gradually reduced so that at September, 1966, only about one quarter of the wells in each pattern, mainly in the outer R-4 and R-5 rings, were being produced continually. On the other hand, Mobil's predictions assume either of two extreme cases: that all wells are produced to a GOR of 50,000, or that only the R-5 wells are produced to the economic limiting GOR which varies from 85,000 to 135,000.

Mobil drew attention to the fact that gas-oil ratios will be

a function of the number and the location of wells being produced at a given stage of depletion. Thus, if all wells are produced, the gas-oil ratios for the pattern as a whole will be higher and nearer its upper predicted curve than if only the outer ring R-5 wells are produced.

Generally speaking in each of the M areas the gas-oil ratios have been increasing more or less continuously since the commencement of fluid injection. The gas-oil ratio for area M-1 was approximately 800 when the solvent injection began in 1959. It decreased and then remained at a level of about 600 during 1961 and since then has climbed progressively to its current level of about 3,000. In area M-2 gas-oil ratios were about 700 and climbed to about 1,000 by mid 1962. They then stabilized and have remained at about 1,200 to the present. In area M-3 gas-oil ratios have increased progressively from a level of about 800 on commencement of the scheme to the current level of around 2,000. In area M-4 the gas-oil ratios were near 1,000 at commencement. They then dropped down to about 700 during 1962 and then climbed and have fluctuated around 2,000 to 3,000 since early 1964. The gas-oil ratio in area M-5 was around 800 when injection of the solvent bank took place in 1961. It has since increased to a level of about 1,300.

Views of Mobil

Mobil presented in graphical form its two predictions of gas-oil ratios versus per cent of oil in place recovered for each M area. Mobil also summarized the current cumulative production and current gas-oil ratio levels in a table presented as follows:

	Oil Production BOPD*	Gas-Oil Ratio CFPB	Cumulative Recovery % of OIP at Start of Pressure Maintenance**
M-1	850	2,860	3.7
M-2	1,672	1,158	4.2
M-3	672	2,058	2.0
M-4	1,046	1,786	2.6
M-5	1,649	1,352	2.8
Total	5,889	1,665	3.1

* Average for June, July and August, 1966

**Cumulative production to August 31, 1966

Mobil concluded on the basis of its comparisons, and having regard to the pattern of production, that the actual gas-oil ratios of patterns M-1, M-3, M-4 and M-5 lie within the prediction range, whereas the gas-oil ratio in pattern M-2 is lower than predicted.

In commenting on the use of gas-oil ratio performance, Mobil cautioned that production history at this point is really too short to draw firm conclusions respecting the efficacy of the schemes. It believed that the cumulative depletion would have to reach a level of 15 to 20 per cent before the gas-oil ratio performance would reflect with some certainty the efficacy of the schemes and the ultimate recovery to be obtained.

Mobil suggested that the lower than predicted gas-oil ratio in the M-2 pattern could be due to the use of an improperly high stratification ratio in its prediction or to the influence of the water slugs which have been injected in the pattern. It observed that the GOR performance of areas M-3 and M-4 lie generally near

its upper prediction curve and it believed that this was probably due to the "gas bubble" effect and the fact that the predicted curves were calculated using relatively low stratification ratios.

Regarding the gas-oil ratios of the R-5 wells, Mobil conceded that in most cases they were significantly higher than predicted. As discussed in Sections III and IX, Mobil attributed these discrepancies to a combination of two things:

(a) more severe stratification in the reservoir than that accounted for in its predictions, and

(b) the gas bubble effect which was not accounted for in the predictions.

Views of Imperial

Imperial contended that sufficient history is now available to show conclusively that the performance of the M areas is alarmingly poor compared to the prediction upon which the design of the process was based. In its opinion current gas-oil ratio levels in M-1 and M-2 clearly indicate the complete failure of these areas to conform to predictions. Whereas Imperial agreed with Mobil that gas-oil ratio performance does not in itself constitute conclusive evidence of the efficacy of the scheme, it emphasized that since the actual gas-oil ratios are much higher than that shown by Mobil in its pilot test this is a strong indication that the schemes have failed. Imperial drew attention to its previous interpretation that the pilot test performance resulted from an immiscible gas displacement within the unconfined 10 acre pilot area combined with recovery of oil from outside the pilot area. Imperial therefore contended that the actual per-

formance of the M areas confirms its previous opinion that the small solvent banks injected in the M areas would soon degenerate, become immiscible, and result in an immiscible gas flood.

Imperial cited the performance of the R-5 wells and stated that for most of them the gas-oil ratios exceed those predicted by Mobil by more than a factor of two and stated also that this discrepancy would be even larger except that the patterns are being affected by adjacent water floods.

Views of British American

British American contended that miscibility in the five M areas broke down very early in the project life and since that time the project has been performing as an immiscible gas drive. The basis for British American's contention was the inordinately high gas-oil ratios and the discrepancy between predictions and performance. British American depicted on maps the gas-oil ratios in the M areas in 1963 and 1965 and from this concluded that GOR performance was poor and that it had been necessary for the operator to remedy the severe gas channelling in the north-west quadrant of M-2 by converting four wells in this area to water injection. British American also submitted, for each M area, a comparison of the actual GOR performance and that which it predicted for an immiscible gas drive. It stated that in all cases the actual recovery is at or below its prediction for immiscible gas displacement. British American concluded that this comparison confirms that miscibility no longer exists in the M areas and that the field performance to date approximates that of an immiscible gas drive.

Views of the Board

The Board believes that the producing gas-oil ratios have been abnormally high and cannot accept Mobil's view that the gas-oil ratio performance has conformed reasonably well to the predictions. Moreover, the Board believes that the differences between performance and prediction would be even greater had it not been for the influence of the adjacent water flood patterns and the fact that in general high gas-oil ratio wells have been either shut in or significantly restricted in production.

The Board agrees with Mobil, as stated in section III, that there are some uncertainties respecting the actual permeability distribution in the reservoir. The Board cannot, however, accept this as adequately explaining the discrepancies between actual and predicted gas-oil ratios. Also, in accordance with its conclusions in Section IX, the Board cannot accept the gas bubble theory as a valid basis for explaining the abnormally high gas-oil ratios. The Board is therefore forced to conclude that the abnormally high gas-oil ratios are in all probability the result of penetration of the solvent bank by injected gas.

Views of the Board Respecting the Overall Performance of M Areas

In the Board's view, the overall performance, i.e. the solvent bank arrivals and the producing gas-oil ratios, confirms that the displacement process in the patterns was occurring much as had been predicted up to the time when the solvent banks had reached most of the R-2 producers. After this time the solvent bank arrivals became difficult to interpret and the gas-oil ratios

increased abnormally. These occurrences convince the Board that the combined effects of viscous fingering, transverse flow, and longitudinal dispersion have had a serious destructive influence on the solvent banks in the most permeable layers at some point beyond the R-2 wells.

The Board concludes that, although the M areas were for some period subject to an effective miscible displacement process, miscibility has now largely broken down in the most permeable layers. The result is that the overall displacement process for all permeability layers must be considered as a combination of miscible and immiscible displacement.

XII BASIS FOR SETTING RECOVERY FACTOR MODIFIERS FOR SOLVENT FLOOD SCHEMES

Introduction

In accordance with the proration plan, recovery factor modifiers (RFM's) are established for the purpose of distributing production allowables within pools subject to more than one form of recovery mechanism. The purpose of the recovery factor modifiers is to permit assignment of allowables to each project in a pool to reflect the recovery mechanism being employed. In the Pembina Cardium Pool recovery factor modifiers have been established for partial gas flood, gas flood, water flood and solvent (miscible) flood. The Golden Spike D-3 A Pool is at present the only other pool in the Province assigned a solvent flood RFM.

Views of Imperial

Imperial submitted that, just as there is no single recovery factor modifier applicable to all immiscible displacement processes within a given pool, no single one is applicable to all miscible displacement processes. For example, one might expect different levels of recovery factor modifiers to be set for conventional water flood, viscous water flood and gas flood schemes within a given pool even though they all fall in the category of immiscible displacement. These differences in level of recovery factor modifier reflect the differences in displacing fluids used and the consequent differences in volumetric conformance and flushing efficiency. Imperial maintained that, to remain consistent with this approach, it seemed reasonable to assign different levels of

of recovery factor modifier to the various types of miscible processes such as solvent slug driven by gas, solvent slug driven by gas and water, sustained solvent injection and sustained alternate solvent and water injection. It expressed the belief that, since each such type of miscible displacement employs a distinct combination of fluids, each type will have a different recovery efficiency. Imperial added that its proposed approach would more fully accomplish the intent of the recovery factor modifier. It felt that, under the current approach in Pembina which assigns the same recovery factor modifier to all types of miscible processes, the operator may be discouraged from implementing a technically sound scheme knowing that schemes of inferior design will be awarded equal status because of a nominal similarity.

Views of Others

The other participants in the hearing made no submissions with respect to the basis for setting recovery factor modifiers where a miscible displacement process is involved.

Views of the Board

The Board believes that each solvent flood can be expected to yield a unique recovery efficiency depending mainly on the size of the solvent bank, the size and shape of the flood pattern, the natural and induced conditions effecting flood instabilities and the destructive effects of viscous fingering, transverse diffusion, and the like. The Board believes that Imperial's recommendation for differentiating between distinct miscible flood processes is reasonable and is appropriate having regard for the intent of the

proration plan. The Board therefore adopts the recommendation and will provide for assigning different recovery factor modifiers for different types of solvent flood schemes.

XIII ULTIMATE RESERVES AND RECOVERY FACTOR MODIFIERS

A. Ultimate Reserves of M Areas

The question of the ultimate reserves attributable to the M areas was not directly considered at the hearing. Nevertheless, with any change in estimates of recovery efficiency, it is necessary for the Board to reconsider the reserves assigned to the M areas. For this purpose, the Board has endeavoured to determine the approximate values for oil in place and ultimate reserves consistent with the views of the participants.

Views of Mobil

Using the hydrocarbon pore volume data provided by Mobil for each quadrant and the analytical data employed by Mobil for each M area, the indicated oil in place at the bubble point is 340 million stock tank barrels (MMSTB). Also applying Mobil's predicted recovery factor for each M area to the indicated oil in place for that area, the ultimate reserves of bubble point oil are 173 MMSTB. An additional 4 MMSTB must be added for oil recovery above the bubble point. On this basis, ultimate reserves for the M areas would be 177 MMSTB and the recovery factor would be 52 per cent. Submissions by the Pembina Allowable Committee, supported by Mobil, have indicated an oil in place for the M areas of 378 MMSTB. Assuming the 52 per cent recovery factor still applied, the ultimate reserves would then be 196 MMSTB for the M areas.

Views of Imperial

In its proposed method of determining the RFM, Imperial suggested assigning reserves of 81 MMSTB due to water flood and

reserves of 4 MMSTB due to solvent injection for the M areas. Its total reserves for the M areas would then be 85 MMSTB which when divided by its suggested oil in place value of 333 MMSTB results in a recovery factor of 25.5 per cent.

Views of British American

British American supported Imperial's approach but did not propose any specific values for oil in place or ultimate reserves.

Board Staff Comparative Estimates

The Board's established original oil in place for the M areas is 357 MMSTB at original reservoir pressure and 352 MMSTB at the bubble point pressure.

The Board staff assumed that the overall recovery process will be a combination of miscible displacement in the early life of the scheme followed by immiscible displacement approximately equivalent to the efficiency of waterflood for the remaining life of the scheme. The estimated water flood recovery factor for bubble point oil is 27 per cent. Recovery due to expansion drive above the bubble point is 1.3 per cent of oil in place or approximately 5 MMSTB.

The Board staff has developed three cases, each based on the Board's figure of 357 MMSTB oil in place at original pressure, intended to span the range of probably recovery efficiency.

Case I

In this case it is assumed that miscible displacement is effected only during the period of solvent bank injection or that under reservoir conditions each barrel of solvent is responsible

for the displacement of one barrel of crude oil. This approach is similar to that proposed by Imperial and British American.

(a) Oil recovery due to solvent bank = 4 MMSTB

(b) Oil recovery by water flood
= (352 - 4) 0.27 = 94 MMSTB

(c) Oil recovery by expansion drive = 5 MMSTB

Estimated ultimate reserves = 103 MMSTB

Estimated recovery factor = $\frac{103}{357} \times 100$ = 29%

Case II

In this case it is assumed that the solvent bank in the most permeable layer was no longer competent after miscibly sweeping the total area of the patterns shown in Table 2, column 3 and that the miscible displacement effected will be proportionately similar in each other layer having regard for the amount of solvent entering each layer. This results in a miscible displacement under reservoir conditions of 7.2 barrels of crude oil for each barrel of solvent injected. On this basis 30 MMSTB of oil would be recovered by miscible displacement.

(a) Oil recovery by miscible displacement = 30 MMSTB

(b) Oil recovery by water flood
= (352 - 30) 0.27 = 87 MMSTB

(c) Oil recovery by expansion drive = 5 MMSTB

Estimated ultimate reserves = 122 MMSTB

Estimated recovery factor = $\frac{122}{357} \times 100$ = 34%

Case III

In this case it is assumed that miscible displacement effected relative to the slug size in each layer will be the same as

that estimated by the Board staff for the most permeable layer. The areas in Table 2, column 5, are assumed to be 100 per cent miscibly swept in the most permeable layer which results in a displacement under reservoir conditions of 2.2 barrels of crude oil for each barrel of solvent injected.

(a) Recovery by miscible displacement = 9 MMSTB

(b) Recovery by water flood
= (352 - 9) 0.27 = 93 MMSTB

(c) Oil recovery by expansion drive = 5 MMSTB

Estimated ultimate reserves = 107 MMSTB

Estimated recovery factor = $\frac{107}{357}$ x 100 = 30%

Previously Established

At December 31, 1965, the Board's established reserves numbers for the M areas were as shown below:

Oil in Place = 357 MMSTB

Ultimate Reserves = 143 MMSTB

Recovery Factor = 40%

When the recovery factor of 40 per cent was assigned, the methods of predicting solvent flood recovery efficiency were not well established and, also, actual experience with the solvent flood schemes in the Pool was very limited. Nevertheless, the Board recognized that recovery by solvent flooding would be greater than that by water flooding. Accordingly, it assigned a recovery factor of 40 per cent for solvent flooding as compared to 30 per cent for water flooding.

Summary of Interpretations

	Oil in Place (MMSTB)		Ultimate Reserves (MMSTB)	Recovery Factor
Mobil (Board staff recapitulation)	340		177	52%
Mobil (Pembina Allowable Committee)	378		196	52%
Imperial	333		85	26%
Board Staff	357	Case I	103	29%
		Case II	122	34%
		Case III	107	30%
Board Previous	357		143	40%

Views of the Board

The Board believes that Mobil's estimated recovery factor of 52 per cent is unrealistic since it is based on the assumption that the area swept in the most permeable layer would be greater than the area within the radius to the R-5 wells. Further it would have to be adjusted downward to conform with what the Board believes is a reasonable economic limit.

The Board cannot accept the approach taken by Imperial and endorsed by British American because the Board is satisfied that the solvent bank did remain intact for some time after the commencement of gas injection. It follows that under reservoir conditions each barrel of solvent must have displaced more than one barrel of crude oil.

Referring to the three cases studied by the Board staff, the Board believes that Case I must be dismissed for the reason mentioned in connection with the position taken by Imperial. Case

II is the maximum attainable since it assumes miscible flooding of the entire pattern. On the other hand, the Board believes Case III, based upon the Board staff minimum figure for the areas swept in the most permeable layer, is pessimistic. As previously mentioned, the Board's best judgment is that the areas swept in the most permeable layers are probably not larger than from one quarter to one third the way between the Board staff swept areas and the total pattern areas. This is equivalent to a displacement ratio of 3.6 barrels of crude oil per barrel of solvent under reservoir conditions. The Board believes that, if such a figure were applied to the total quantity of solvent injected, i.e. to all the permeability layers, it would yield a fair assessment of the overall miscible displacement recovery. This is equivalent to assuming that 4.2 per cent of the original oil in place is effectively miscibly swept by a 1.2 per cent solvent slug. Applying such a figure as indicated and assuming that the remainder of the pattern would be subject to immiscible displacement at a recovery factor of 27 per cent, an overall recovery factor of 31 per cent results, which the Board believes appropriate. The Board will continue to apply its previously established original oil in place figure of 357 million stock tank barrels. The resulting ultimate reserves assigned to the M areas are 111 million stock tank barrels.

B. Recovery Factor Modifier for M Areas

Views of Mobil

Mobil proposed a solvent flood RFM of 5.49 based on a pool average solvent flood recovery of 61.3 per cent as compared with

the Board established primary recovery of 11.4 per cent. Mobil employed seven permeability feet ranges similar to that used by the Pembina Allowable Committee and assumed one per cent solvent banks, 41-spot patterns and intermittent injection of gas and water.

Views of Imperial

Imperial recommended a recovery factor modifier of 2.24 for the M areas. Using the Board's assigned water flood recovery factor of 0.243 and primary recovery factor of 0.114, Imperial determined the RFM as follows:

$$\text{RFM} = \frac{\text{Water Flood Reserves + Recovery Due to Solvent}}{\text{Primary Reserves}}$$

Oil in Place = 333 MMSTB

$$\text{RFM} = \frac{81 \times 10^6 + 4 \times 10^6}{38 \times 10^6} = 2.24$$

Views of British American

British American agreed with the recovery factor modifier recommended by Imperial.

Board Staff Comparative Estimates

The Board staff estimated the probable range of pool average recovery factors using approaches similar to those employed for estimating ultimate reserves for the M areas.

The RFM was calculated using the following formula:

$$\text{RFM} = \frac{\text{Recovery Due to Oil Expansion} + \text{Recovery Due to Miscible Displacement} + \text{Recovery Due to Water Flood}}{\text{Recovery Due to Primary Depletion}}$$

For convenience, the following terms are defined:

N = oil in place at original reservoir pressure

N_{pb} = oil in place at the bubble point

N_{pb} = 0.987 N

Recovery due to expansion of oil down to the bubble point = 0.013 N

Recovery by water flooding at the bubble point = 0.23 N_{pb}

Recovery by primary depletion = 0.114 N

Solvent bank volume as a fraction of oil in place at bubble point = 0.012 N_{pb}

Case I

Assumptions as in Case I respecting ultimate reserves of M areas.

$$RFM = \frac{0.013\ (N) + 0.012\ (0.987\ N) + 0.23\ (1 - 0.012)\ 0.987\ N}{0.114\ N}$$

$$= 2.18$$

Case II

Assumptions as in Case II respecting ultimate reserves of M areas.

$$RFM = \frac{0.013\ (N) + 0.012 \times 7.2\ (0.987\ N) + 0.23\ (1 - 0.012 \times 7.2)\ 0.987\ N}{0.114\ N}$$

$$= 2.68$$

Case III

Assumptions as in Case III respecting ultimate reserves of M areas.

$$RFM = \frac{0.013\ N + 0.012 \times 2.2\ (0.987\ N) + 0.23\ (1 - 0.012 \times 2.2)\ 0.987\ N}{0.114\ N}$$

$$= 2.28$$

Previously Established

The previously assigned RFM for solvent floods in the Pembina Cardium Pool was 3.51.

Views of the Board

The Board believes, as it indicated previously in its discussion of ultimate reserves of the M areas, that Mobil's approach yields a recovery estimate unrealistically high, whereas Imperial's approach results in too low a figure. Consistent with its previous findings the Board believes that, for the process used in the M areas, a suitable value for the miscible displacement under reservoir conditions is 3.6 barrels of crude oil displaced per barrel of solvent injected. This results in a pool average recovery factor of 27.3 per cent and a solvent flood RFM of 2.40 which the Board adopts for the M areas of Approval No. 877 effective May 1, 1967(1).

C. Recovery Factor Modifier for Area S-W (Lobstick)

Views of Pan American

Pan American proposed a solvent flood RFM of 3.9 based upon a primary recovery of 12.1 per cent and a solvent flood recovery of 46.9 per cent. Pan American employed the basic data, seven kh capacity ranges, economic limit, and so forth as submitted at previous reserves hearings by the Pembina Allowable Committee.

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(1) The Board found it necessary to announce an RFM for the M areas in mid-April, 1967, in preparation for the May, 1967, proration calculations. The figure announced was 2.63. On final checking in connection with the completion of this report a computational error was found. The corrected figure of 2.40 was announced by amendment of the MD order issued May 1, 1967.

It assumed a 3 per cent solvent bank preceded by a water slug and followed intermittently by gas and water slugs. For uniform flood front advance, Pan American calculated 56.2 per cent weighted average recovery. Allowing for the effects of fingering built into its calculation method, Pan American determined the weighted average recovery to be 46.9 per cent.

Views of Others

Mobil expressed the view that Pan American's method provides a recovery factor estimate which is arbitrarily conservative.

Board Staff Comparative Estimates

Pan American has developed a relationship[7] established on the basis observed by laboratory linear flood systems to show longitudinal mixing as a function of viscosity difference, viscosity ratio and distance travelled. The relationship is as follows:

$$S = \left(\frac{1000\,\Delta\mu}{R\,\mu_1/\mu_2}\right)^{\frac{1}{2}} \qquad (1)$$

S = solvent volume, per cent hydrocarbon pore volume within radius R,

R = radius to which miscibility is maintained, feet,

μ_1 = viscosity of displacing fluid, centipoise,

μ_2 = viscosity of displaced fluid, centipoise, and

$\Delta\mu$ = difference between the viscosities of the displaced and displacing fluids, centipoise.

To allow for non-uniform advance or fingering of the injected fluid, the solvent volumes were arbitrarily doubled so that the

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(7) Hall, H. N., and Geffin, T. M.: "A Laboratory Study of Solvent Flooding," Trans., AIME (1957), Vol. 210, 48.

equation becomes

$$S = \left(\frac{4000\Delta\mu}{R\mu_1/\mu_2}\right)^{\frac{1}{2}} \qquad (2)$$

In its submission Pan American stated "that some allowance should be made for fingering and that equation 2 is the more applicable in determining the extent of miscibility. However, depending upon the effectiveness of the injected water in maintaining a uniform flood front advance as indicated by field performance, it is possible the recovery may approach that described by equation 1."

Although Pan American, in its predictions, endeavours to account for viscous fingering, it does not appear to make any provision for other adverse effects such as transverse molecular diffusion and transverse flow due to pressure gradients. Arbitrary allowance may be made for these additional adverse effects assuming the perimeter of the mixing zones to be greater than that corresponding to equations 1 or 2. From this point of view, Pan American's equation 1 may be considered as the 2π case and Pan American's equation 2 as the 4π case. The Board staff has evaluated a 6π and an 8π case. From the "radii from which miscibility is maintained," so determined, the staff calculated the overall recoveries which would result. These recoveries decreased rapidly as the perimeter was increased from the 2π to 4π case, but only slowly thereafter. In other words, Pan American's calculations using equation 2 appear to have made allowance for the bulk of the factors adversely influencing miscible flood recovery.

RFM Estimates

For comparative purposes, the Board staff has made two sets of calculations.

Case I

For Case I the Board staff has assumed that Pan American's proposed pool average recovery factors can be properly adjusted to reflect the actual solvent slug size employed in Lobstick and also to reflect the Board decision respecting water flood recovery efficiency pursuant to the February, 1966, reserves hearing.

Pan American's pool average recovery factors of 46.9 per cent and 56.1 per cent are based on a 3 per cent solvent slug. By comparison the actual solvent slug employed in Lobstick is 2.64 per cent of hydrocarbon pore volume. According to the predictions provided by Pan American for Lobstick, a 2.64 per cent slug would generate 41 per cent recovery, compared with 42.8 per cent recovery for a 3 per cent slug.

Following the reserves hearing in February, 1966, the Board established water flood reserves for the Pembina Cardium Pool of 1,260 MMSTB, whereas the Pembina Allowable Committee, whose numbers are determined on the same basis as Pan American's, submitted a value of 1,580 MMSTB. The difference between 1,260 and 1,580 reflects the differences of opinion respecting economic limit, methods of averaging, and so forth.

Making the appropriate adjustments to reflect solvent slug size and the Board's previous decision, the following values result:

$$\text{Probable:} \quad 46.9\% \left(\frac{41.0}{42.8}\right) \left(\frac{1,260}{1,580}\right) = 36.0\%$$

$$\text{Possible:} \quad 56.1\% \left(\frac{41.0}{42.8}\right) \left(\frac{1,260}{1,580}\right) = 43.0\%$$

Case II

For Case II the Board staff estimated recovery efficiency consistent with the experience obtained in the M areas.

As a first approach, it may be simply assumed that the miscible displacement under reservoir conditions would be 3.6 barrels of crude oil displaced per barrel of solvent injected. Using this value and having regard for the 2.64 per cent solvent bank injected in Lobstick, the staff calculates a pool average recovery factor of 31.2 per cent.

Another approach is to determine the value of K in the equation $S = \left(\frac{K \Delta\mu}{R \mu_1/\mu_2}\right)^{\frac{1}{2}}$ on the basis of the recovery efficiency now expected for the M areas. Using this approach and applying the size of solvent slug used in Lobstick, miscible displacement under reservoir conditions was estimated to be approximately 4.6 barrels of crude oil displaced per barrel of solvent injected. This results in a pool average recovery factor of 33.2 per cent.

Views of the Board

The Board agrees with its staff that the figures submitted by Pan American as probable and possible recovery factors require downward adjustment on account of slug size and to bring them in line with the Board's views respecting ultimate reserves by water flood. It considers the Board staff calculations, resulting in adjusted Pan American figures of 36 and 43 per cent, to be reasonable for this purpose. Referring to the Board staff calculation using the generalized form of the Pan American equation and a

value of K based on the performance of the floods in the M areas, the Board recognizes that the resulting 33.2 per cent recovery factor does not allow for the probable beneficial effects of the controlled pre-injection of water. Having this latter in mind, the Board believes that a reasonable pool average recovery factor for the type of scheme operating in Lobstick is 36 per cent. This is also the lower limit of the Board staff adjusted Pan American figures. The Board therefore adopts this number and accordingly assigns a solvent flood RFM of 3.16 for area S-W of Approval No. 631 effective May 1, 1967(1).

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(1) The Board found it necessary to announce an RFM for area S-W (Lobstick) in mid-April, 1967, in preparation for the May, 1967, proration calculations. The figure announced was 3.68. On final checking in connection with the completion of this report a computational error was found. The corrected figure of 3.16 was announced by amendment of the MD order issued May 1, 1967.

XIV OVERALL FINDINGS OF THE BOARD

The Board and its staff have given careful consideration to the evidence and opinions expressed at the hearing held during November, 1966, for the purpose of reviewing the efficacy of the solvent flood operations in areas M-1, M-2, M-3, M-4 and M-5 in the Pembina Cardium Pool and the level of solvent flood recovery factor modifier for the Pembina Cardium Pool. The findings of the Board with respect to these matters are as follows:

(a) The Efficacy of the Solvent Flood in the M Areas

Having regard for the producing gas-oil ratio performance, the evidence of monitoring solvent bank arrival and general reservoir engineering considerations, the Board finds that, while the five M areas were for some time subject to a fully effective miscible displacement process, miscibility has now broken down in the most permeable layers. The Board believes that the overall displacement process for the life of the scheme and for all permeability layers must be considered as a combination of miscible and immiscible displacement. The views of the parties and of the Board respecting this matter are contained in Sections III to XI of this report.

(b) Basis for Determination of Solvent Flood Recovery Factor Modifiers

The Board finds that each type of solvent flood scheme may be expected to yield a unique recovery efficiency depending mainly on the size of the solvent bank, the size and shape of the flood pattern and the natural and induced conditions affecting flood

instabilities. The Board therefore will assign different recovery factor modifiers for solvent flood schemes of different effectiveness. The views of the parties and of the Board respecting this matter are contained in Section XII.

(c) The Recoverable Reserves for the M Areas

The Board finds that some 4 per cent of the original oil in place in the M areas will be recovered by a miscible displacement process and that the remaining oil will be subject to recovery by an immiscible gas or water displacement process. Accordingly the Board finds that the combined recovery efficiency will be 31 per cent of the 357 MMSTB oil in place and assigns ultimate reserves of 111 MMSTB. Details respecting the determination of the ultimate reserves for the M areas are contained in Section XIII.

(d) The Solvent Flood Recovery Factor Modifier for the M Areas

The Board finds that the appropriate solvent flood recovery factor modifier for the M areas is 2.40 to be effective May 1, 1967. The details of the RFM calculations for the M areas are contained in Section XIII.

(e) The Solvent Flood Recovery Factor Modifier for Area S-W (Lobstick)

The Board finds that the appropriate solvent flood recovery factor modifier for the Area S-W (Lobstick) is 3.16 to be effective May 1, 1967. The details of the RFM calculations for Area S-W (Lobstick) are contained in Section XIII.

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(c) The Reed-Solomon recovery for the M disks

The Board finds that some 4 bit code of the original bit
pattern has become corrupted. Accordingly the
processor has input the remaining bit will be applied to recovery by
replace it the M disks will be recovered by a multiple disablement
of III MMSIM.

(d) The Board finds that the appropriate solvent flood recovery
factor modifier for the M disks is 2.45 to be applied MWh 1.
contained in section XIX.

Note: The details of the RAM calculations for the M disks are
given in section XIX.

(e) The Board finds that some 5 bit code of the original bit
pattern has become corrupted by a multiple disablement
of III MMSIM.

The Board finds that the appropriate solvent flood recovery
factor modifier for the M disks is 2.45 to be applied MWh 1.

(f) The solvent flood recovery factor modifier
for the M disks

The Board finds that the appropriate solvent flood recovery
factor modifier for solvent flood schemes of different
insensitivities. The Board considers that
[illegible] different

(g) The solvent flood recovery factor modifier
for disks S-M (Dopelick)

The Board finds that some 8 bit code of the original bit
pattern has become corrupted in section XIX.